EXPERIMENTAL EVIDENCE OF THE INFLUENCE OF PLASTICITY AND SURFACE-ROUGHNESS ON FATIGUE CRACK-CLOSURE PHENOMENON IN VACUUM

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ABSTRACT

Fatigue tests with a decreasing stress intensity amplitude down to the threshold were performed in vacuum on CT specimens in four age-hardening 7075 Aluminium alloys, and for two values of load ratio. Crack closure measurements (by compliance and potential drop methods) were made at threshold and compared with the aspect of the crack on the side of the specimen. A correlation is made between the plastic deformation aspect observed along the crack, the crack surfaces roughness and the residual spacing measured between the edges of the crack at zero load. These results are discussed in terms of plastic strain and roughness history during the test, which must be taken in account to understand the localization of crack closure and the length of crack over which it was observed.

KEYWORDS

Fatigue. Threshold. Vacuum. Crack closure.

INTRODUCTION

The crack closure model, first developed by Elber (1970), attempts to explain spectrum loading fatigue crack growth in terms of the effective stress intensity range, ΔK_{eff} for which the crack is open. Crack closure was first considered to arise from the fact that, during crack advance, material is plastically strained at the crack tip and, due to the restraint of surrounding elastic material on this residual stretch, some closure of the crack occurs above the minimum load of the fatigue cycle. Recent studies pointed out that a second mechanism, termed roughness-induced crack closure, (Minakawa, 1981), arises in situations where the size-scale of the fracture surface roughness is comparable to crack tip displacements and where significant Mode II displacements exist, e.g. at near threshold levels (Davidson, 1981). Models for fatigue crack closure based on surface roughness (Suresh,1982) and residual strain (Granville Sewell, 1977) were proposed that would permit to calculate ΔK_{eff} in some simple configurations in vacuum. The purpose of the present study is an attempt to experimentally state the influence of loading history and roughness configuration all along a fatigue crack on the amount of crack closure.

EXPERIMENTAL RESULTS

Experimental Conditions

Fatigue tests were carried out on CT specimens of 75 mm width and 12 mm thickness, using an Instron electro-hydraulic fatigue testing machine equipped with a vacuum chamber in which a pressure less than 10^{-3} Pa can be obtained. A vacuum environment was chosen to avoid any oxyde-induced crack closure. The crack propagation was obtained by a series of load drops down to the threshold at a constant load ratio (R) value, and frequency of 40 Hz. In fig.1 is schematically shown the wake of residual strain left behind, as the crack grows. Two values of load ratio were investigated : R = 0.1 and R = 0.5 and an industrial Aluminium alloy (7075 Al alloy) in four aged hardening conditions was chosen because of the very different crack surfaces roughness previously observed in these conditions (Lafarie-Frenot, 1983). In Table I are summarized the properties of these alloys.

TABLE I - Age-hardening conditions properties

Symbol used in this study	A	B	C	D
Heat Treatment	T 351 Underaged	T 651 Peak-aged	T 7351 Over-aged	24 h at 200 Hyperoveraged
Hardening precipitation	GP zones+M' Shearable Coherent	M'(+M+T') Shearable Coherent	M + T' Partially shearable Semi-coherent	M Unshearable Incoherent

When a crack propagation of a few 10^{-8} mm/cycle was obtained, variations of compliance (measured by a back face strain gauge) and of potential drop amplitude were recorded during the last loading-cycle using a digital oscilloscope and a X - Y recorder.
The specimen was then taken off the testing machine and the crack observed with an optical microscope. A lot of microphotographs have been made along the whole crack and have permitted to :

- i : Describe and analyse the aspect of plastic zone accompanying the crack ;
- ii : Characterize the roughness of the crack by its sinuosities on the edge of the specimen ;
- iii : Measure the evolution of the spacing between the two edges of the crack from the notch to the tip, for a load equal to zero.

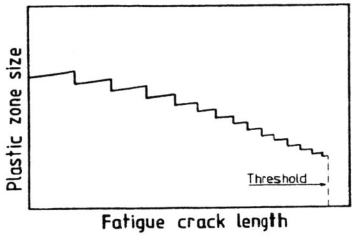

Fig.1 : Schematic representation of the plastic zone size evolution along the crack during a fatigue crack propagation threshold test.

Results

The crack surfaces roughness can be correlated with the aspect of the strained zone of the material very close to the crack surfaces. This aspect is varying with the microstructure of the alloy, the crack propagation rate (da/dN) and the load ratio (R). Two different mechanisms of plastic deformation and fracture were observed, noted respectively Type I for the underaged alloy (A) and Type II for the hyperoveraged alloy (D), whatever R :

- i : Type I : Many straight and fine slips lines are observed along the crack for mean crack propagation rates (10^{-4}mm/cycle > da/dN > 10^{-6} mm/cycle). Two systems are often active and create like a substructure near the crack. The crack advances alternatively from one slip plane to another one which produces little asperities on the crack surfaces (Fig.2). When the crack growth rate decreases, the number of active slip systems in each grain decreases too, and the crack length in each slip plane becomes longer. Because of the orientation of active slip plane in the grain,the crack sometimes grows close to the loading axis ; in the near-threshold range, finally appear many secondary microcracks, as if the crack tries to find its way (fig.3). An attempt to quantify the crack surface roughness has been made by the parameter γ as defined first by Suresh (1982) and schematically represented in fig.4. For the A condition, γ is increasing from about 0.3 for da/dN $\approx 10^{-4}$mm/cycle to 0.7 for da/dN < 10^{-7}mm/cycle.
  However, it must be noted that there exists a great scatter on the values of γ obtained in two adjacent grains, particularly because of the non-symmetrical aspect of the sinuosities, and that the amplitude of asperities (noted h on fig.4) seems to be necessary for a good description of the roughness. Finally, we can say that, for the underaged Al alloy, the fracture surface roughness is high and that it increases as the crack growth rate decreases.

- ii: Type II : The crack is accompanied by a wake of strained material which is formed by little wings, looking like plastic zone created by an overload (Ranganathan, 1983) .The crack often advances alternatively from a right wing to a left one, creating little asperities (Fig.5) ; the mean direction of the crack is always remaining perpendicular to the loading axis. In the hyper overaged alloy (D), where this type of plastic deformation and crack advance is observed, the crack surfaces roughness is always low and decreases - γ varying from 0.06 to 0 - with the crack growth rate from 10^{-4} mm/cycle to 10^{-7} mm/cycle.

The peak-aged (B) and over-aged (C) Al alloys present either Type I or Type II plastic deformation and crack advance, sometimes a mixed one (noted Type I + II) because of transitions in crack growth mechanisms with crack growth rates, previously observed (Lafarie-Frenot, 1983). The associated crack surfaces roughness is rapidly increasing when such a transition from Type II to Type I occurs (e.g. γ is varying from 0.1 to 0.65 for the B condition at R = 0.1 down to the threshold).

These results are summarized in Table II.
The observations of the residual spacing between the two crack edges for a load equal to zero, primarily point out that, when the roughness is high, the crack is not continuously closed, but only where the crack presents acute angles and a direction close to the loading axis (Fig.3). On the contrary, when the crack path is flat, crack closure appears localized on longer crack lengths (Fig.6).

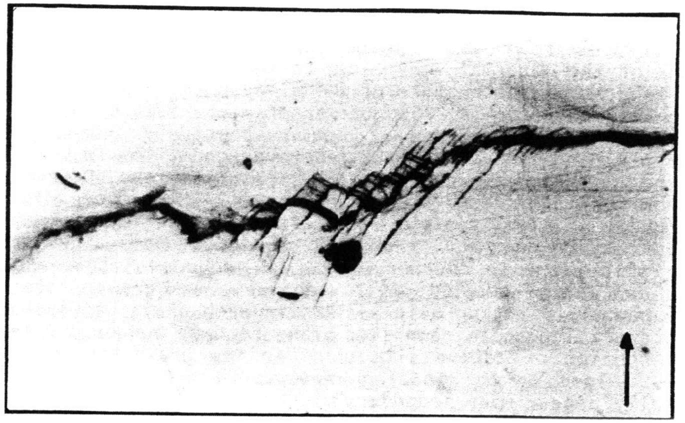

Fig.2 - Typical aspect of Type I mode of plastic deformation and fracture in the mid-range of FCGR. The arrow indicates the loading axis. (Peak-aged 7075 Al alloy, R = 0.5, da/dN = 5×10^{-5} mm/cycle).

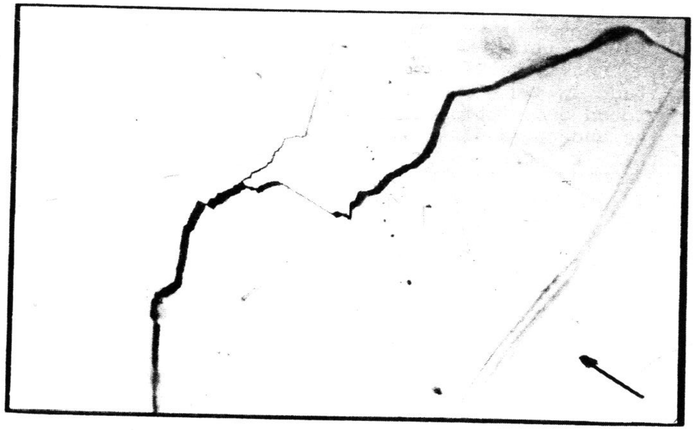

Fig.3 - Aspect of a near threshold fatigue crack in the underaged 7075 Al alloy (R = 0.1, da/dN = 10^{-7} mm/cycle). The arrow indicates the loading axis.

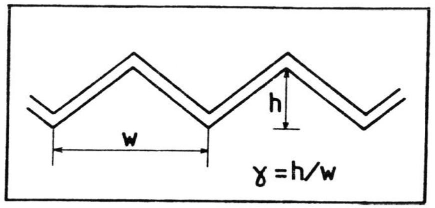

Fig.4 - Schematic representation of a near-threshold fatigue crack (Type I) as proposed by Suresh (1982).

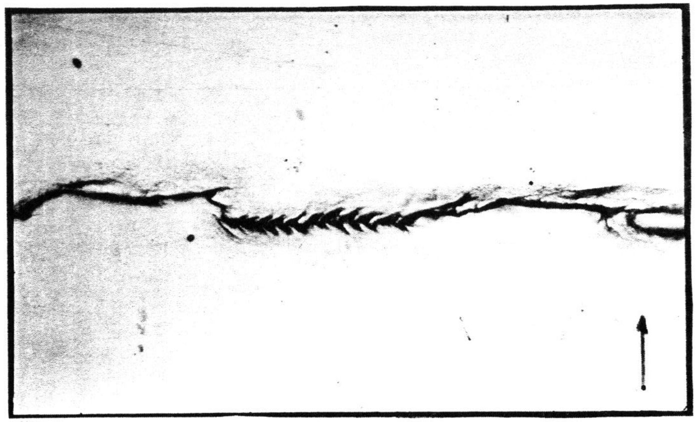

Fig.5 - Typical aspect of Type II mode of plastic deformation and fracture in the mid-range of FCGR. The arrow indicates the loading axis. (Hyper-overaged 7075 Alalloy : R = 0.5 ; da/dN = 8×10^{-5} mm/cycle).

TABLE II - Characteristic features of crack propagation as observed on the side of the specimen after the test from the notch to the threshold (Crack surface roughness is characterized by Low, Mean, High, Very High)

Alloy	A		B		C		D	
R ratio	0.1	0.5	0.1	0.5	0.1	0.5	0.1	0.5
Plastic strain wake type	I	I	I+II ↘ I	I+II ↘ I	II ↘ I	II ↘ I	II	II
Crack surfaces roughness	H. ↗ V.H	H. ↗ V.H	M ↗ V.H	M ↗ V.H	L → M	L → H	L ↘ L	L ↘ L
Crack growth rate da/dN (mm/cycle)	↘	↘	↘ 3×10^{-5} ↘	↘ 5×10^{-5} ↘	↘ 10^{-7} ↘	↘ 4×10^{-7} ↘	↘	↘
Crack length a (mm)			30	26	36	31.5		

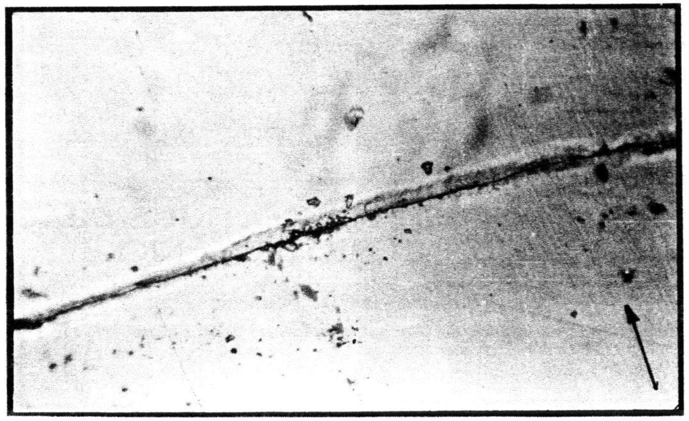

Fig.6 - Aspect of a closed and flat fatigue crack in the hyper-overaged 7075 Al alloy (R = 0.1 : $da/dN = 8\times10^{-7}$ mm/cycle). The arrow indicates the loading axis.

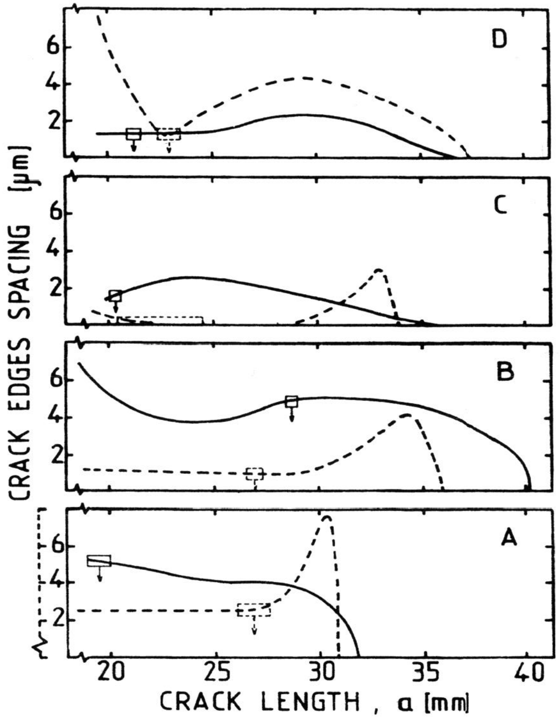

Fig.7 - Average profiles of the residual spacing between the crack edges in the four aged-hardening conditions and for the two values of load ratio (Solid lines R = 0.1 ; dashed lines R = 0.5). Scatter bands on the curves give the value of a* deduced from crack closure measurements.

On the microphotographs of the crack, measurements of the mean residual spacing between its edges have been made with a maximal scatter of $\pm$ 1 µm. In fig. 7 are presented the average profiles of the residual spacing between the crack edges in each case of aged condition and load ratio for a load equal to zero. The values of equivalent crack length at zero load (noted a*),obtained by reporting on the calibration curves (compliance α vs crack length a, and potential drop amplitude ΔV vs crack length a) the measured values of α_o and ΔV_o at zero load, are plotted with their scatter on these curves. These values show that, for the strain gauge and the voltmeter, the crack is almost totally closed at zero load, though the crack is still observed open in the vicinity of the crack tip, particularly for R = 0.5. In this case, an increasing residual spacing between the two crack edges is observed near the crack tip for the B and C conditions, which corresponds to the transition from type II to type I mode of failure described above. Note that the values of residual spacing obtained for the crack A at R = 0.5 are only relative ones, because of an accidental overload occurring at the end of the test, which holds the crack open.

DISCUSSION

The slips observed near the crack and described as Type I, correspond to a crystallographic mode of failure, by shearing along a slip plane, the number of active planes decreasing with the crack growth rate. This observation is in accordance with the facets observed on the microfractographies made in these alloys (Lafarie-Frenot, 1983). In this case the crack surfaces roughness is very important and the closure occurs only at acute angles and where the crack growth direction is close to the loading axis ; this localization prevents a surfaces closeness elsewhere, which leads to an important average residual spacing between them, although the crack closure is intense (e.g. for the under-aged and peak-aged alloys, and R = 0.1).

The deformation mode described as Type II and the associated crack propagation mode which can be described as a tearing of a plastic zone wing, may be interpreted in terms of cumulated plastic strains. In the hyper-overaged alloy where the hardening precipitates cannot be sheared by dislocations, the slips distribution is relatively homogeneous, the strained material can be thus considered as isotropic and tears where the strain is the highest. The crack advances by successive leaps, the amplitude of which can get down to 5 µm. When the crack is stopped, a new plastic zone must be created before it propagates again. Such a cumulated plastic strain criterium is in accordance with the ductile fractographic aspect of the hyper-overaged alloy (Lafarie-Frenot, 1983). The mean path of the crack remains perpendicular to the loading axis, which leads to low surfaces roughness. The closure concerns long crack lengths and leads to very low, close to zero, residual spacing between the crack edges all along the crack in the hyper-overaged alloy fatigued at R = 0.1.

When the age-hardening condition leads to intermediate and transitional mechanisms of fracture down to the threshold, the surfaces roughness is much varying with the values of the stress intensity amplitude and load ratio. Thus, the residual spacing along the crack at zero load is much influenced by the crack surfaces roughness history (i.e. evolution along the crack), and load ratio. In peak-aged alloy (B), the residual spacing observed near the crack tip, both for R = 0.1 and R = 0.5 is explained by the high surfaces roughness observed near threshold, and the difference with R of spacing values near notch tip is explained by the higher residual stresses at zero load in the specimen tested at R = 0.5 than at R = 0.1.

There is a good qualitative agreement between the amount of crack surfaces roughness and crack edges spacing observed in almost every case. However it is not true for the D condition tested at R = 0.5 for which a flat aspect of the surfaces was always observed, which might lead to low and uniform values of residual spacing. The closure point at a = 23 mm corresponds to the crack length for which the stress intensity amplitude value, and thus plastic zones size, were the highest during this test. This observation points out that the loading history, by the wake of residual strain left behind the crack tip, has a great influence on the amount of crack closure, when the crack tip displacement is small, e.g. at near-threshold level. That explains that, during a test with a decreasing stress amplitude, one observes an increasing amount of crack closure when the crack tip displacement becomes of the order of the crack surfaces roughness (Lafarie-Frenot, 1983). Furthermore, the plastic elongation along the crack is more important near the notch and induces preferentially crack closure in this region, especially when the crack surfaces roughness is low along the whole crack.

CONCLUSIONS

i - Fatigue tests conducted in vacuum on a 7075 Al alloy have permitted to characterize two types of plastic deformation and fracture mode which depend on the heat-treatment.

- in the under-aged alloy, fracture by shearing along slip planes leads to high values of crack surfaces roughness. In such a case, the crack closes only at acute angles and where the crack path is close to the loading axis.
- in the hyper-overaged one, fracture by tearing a plastic zone wing induces a very flat aspect of the crack, particularly near the threshold. The closure then concerns long lengths of the crack.

ii - The localization and the amount of crack closure much depends on the crack surfaces roughness evolution during the test and the loading history (i.e. load ratio and plastic elongation of the material near the crack surfaces from the notch to the crack tip).

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